A Prototype AMSR-E Global Snow Area and Snow Depth Algorithm

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***Abstract*—A methodologically simple approach to estimate snow depth from spaceborne microwave instruments is described. The scattering signal observed in multifrequency passive microwave data is used to detect snow cover. Wet snow, frozen ground, precipitation, and other anomalous scattering signals are screened using established methods. The results from two different approaches (a simple time and continentwide static approach and a space and time dynamic approach) to estimating snow depth were compared. The static approach, based on radiative transfer calculations, assumes a temporally constant grain size and density. The dynamic approach assumes that snowpack properties are spatially and temporally dynamic and requires two simple empirical models of density and snowpack grain radius evolution, plus a dense media radiative transfer model based on the quasicrystalline approximation and sticky particle theory. To test the approaches, a four-year record of daily snow depth measurements at 71 meteorological stations plus passive microwave data from the Special Sensor Microwave Imager, land cover data and a digital elevation model were used. In addition, testing was performed for a global dataset of over 1000 World Meteorological Organization meteorological stations recording snow depth during the 2000–2001 winter season. When compared with the snow depth data, the new algorithm had an average error of 23 cm for the one-year dataset and 21 cm for the four-year dataset (131% and 94% relative error, respectively). More importantly, the dynamic algorithm tended to underestimate the snow depth less than the static algorithm. This approach will be developed further and implemented for use with the Advanced Microwave Scanning Radiometer—Earth Observing System aboard Aqua.**

***Index Terms*—Dense media radiative transfer model, microwave radiometry, remote sensing, snow depth.**

I. Introduction

SNOW COVER estimation is important for climate change studies and successful water resource management. It has been shown that snow cover can affect directly climate dynamics [1], and so our ability to estimate global snow coverage and volumetric storage of water in seasonal and permanent snowpacks impacts on our ability to monitor climate and climate change and to test climate model simulations. Furthermore, successful estimation of volumetric storage of snow water at a basin scale should improve the management of water supply. Remote sensing has been used to monitor continental scale seasonal snow covers for 25 years [2] with much of this effort focused on the use of remote sensing of snow cover area using visible and infrared sensors [3], [4]. While this effort is starting to mature, the successful estimation of global snow volume [snow depth or snow water equivalent (SWE)] is still at a developmental stage.

Progress in retrieving snow depth or SWE has been made through the available "instruments of opportunity" such as the Scanning Multichannel Microwave Radiometer (SMMR) and the Special Sensor Microwave Imager (SSM/I). Neither instruments were designed explicitly for snow applications but have been found to be effective for this application [5], [6]. For snow detection, passive microwave instruments tend to underestimate the snow area compared with estimates from visible-infrared snow mapping methods [7]. Additionally, the errors of estimates of snow volume tend to be large with standard errors of 20 mm SWE and greater not uncommon (e.g., see [8]). The perceived need by water resource managers and land surface and climate modelers is for high accuracy, local scale estimates of snow volume on a daily basis. Unfortunately, the spatial resolution of the SMMR and SSM/I instruments tends to restrict their effective use to regional-scale studies. Furthermore, currently available SSM/I data is acquired twice daily only at high latitudes with coverage more restrictive at lower latitudes. The Advanced Microwave Scanning Radiometer—Earth Observing System (AMSR-E) aboard Aqua, which was launched in 2002, should help to overcome some of these drawbacks. Table I gives selected details of the AMSR-E and SSM/I configurations and while AMSR-E temporal coverage is similar, its spatial the resolution is generally finer than that of the SSM/I. Overall, technological improvements should be matched by the improvements in snow cover estimation. However, there is a need to develop a global snow monitoring algorithm (area and volume) that is temporally and spatially dynamic so that current retrieval errors can be reduced further.

This paper describes the development and testing of an algorithm to estimate global snow cover volume from spaceborne passive microwave remote sensing observations. Our aim is to detect snow cover area globally and then to estimate the snow depth for the snow area. The microwave brightness temperature emitted from a snow cover is related to the snow mass which can be represented by the combined snow density and depth, or the SWE (a hydrological quantity that is obtained from the product of snow depth and density). Two issues emerge from this relationship that require some consideration. The first is theoretical

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TABLE I
COMPARISON OF AQUA AMSR-E [9] AND SSM/I SENSOR CHARACTERISTICS [10]

AMSR-E	**Center Freq (GHz)**	**6.9**	**10.7**	**18.7**	**23.8**	**36.5**	**89.0**
	Band Width (MHz)	350	100	200	400	1000	3000
	Sensitivity (K)	0.3	0.6	0.6	0.6	0.6	1.1
	IFOV (km x km)	76 x 44	49 x 28	28 x 16	31 x 18	14 x 8	6 x 4
SSM/I	**Center Freq (GHz)**			**19.35**	**22.235**	**37.0**	**85.5**
	Band Width (MHz)			240	240	900	1400
	Sensitivity (K)			0.8	0.8	0.6	1.1
	IFOV (km x km)			69 x 43	60 x 40	37 x 29	15 x 13

in nature and the second is of a practical consideration. First, in regions where SWE data are sufficiently available, microwave algorithms have been developed to estimate SWE (e.g., [8] and [11]). To estimate snow depth alone using passive microwave observations, assumptions about the snow density need to be made because microwave radiation is sensitive to both depth and density and not just one variable alone. This is the reason why previous "static" algorithms have worked reasonably well for average seasonal and global snow depth estimation. At the local scale, however, and over short time periods, estimates have been subject to errors as a result of rapid changes in internal snowpack properties (density, layering) to which the microwave response is sensitive. Thus, the implication is that algorithms should be developed to estimate not snow depth but SWE which is a bulk property of the snowpack that directly influences the microwave response. Second, however, and counter to the first issue, is that on a practical level and for the validation of a global algorithm there are consistently and considerably fewer global SWE measurement sites than there are snow depth measurement sites. One could develop a SWE algorithm but there are so few data globally available with which to test the estimates so that traditional validation would be a problem. In this paper, therefore, in the absence of global SWE validation datasets, our effort is concerned on a practical level with snow depth estimation, which has a greater global validation potential.

VI. CONCLUSION

A dynamic approach to retrieve global snow depth estimation is presented. Compared with static approaches developed in the past, the dynamic algorithm tends to estimate snow depth with greater RMSE values but lower ME values (bias). These results are promising, but there is a need for further improvement and refinement to the algorithm especially in terms of identifying and reducing the elements of the models that contribute to large errors. The dynamic model builds on original work by Chang *et al.* [5], Foster *et al.* [13], and Tsang *et al.* [38]. In essence, it adjusts the coefficient in (1) by predicting how the grain size might vary and how this affects the emission from a snowpack. In addition, by incorporating a time smoothing function, the estimates are made temporally dependant. The algorithm can still be improved, however. Refinement is needed to the grain size and volume fraction evolution models since its empirical functions are space independent; Sturm and Holmgren [40] have shown that a seasonal snow cover classification is possible based on dominant geographically varying snow climatology. This information could be used further to improve the parameterization of (2). In addition, the planned Moderate Resolution Imaging Spectroradiometer (MODIS) snow albedo product could potentially be of great help with the grain size evolution. A snowpack's surface grain size can be related to its albedo and this information could be very useful especially at the start of the season when snow grain sizes are critical for the model. Also, the density model is very simple and needs further refinement to account for variable changes to snow density. This is more problematic, but could be addressed using a multisensor approach to determine more accurately the snow surface thermal environment.

With the availability of AMSR-E data, some of the snow depth retrieval problems should be reduced. For example, with AMSR-E's improved spatial resolution, snow detection capabilities ought to improve especially for the identification of shallow snowpacks at the start of the season. Although these early season packs are not as hydrologically significant as the midseason packs, they can influence the evolutionary characteristics of the snow, which are important for microwave retrievals. In addition, with AMSR-E's expanded range of channels at lower frequencies, characterization of the subnivean snow surface should improve, and it is possible that there will be potential for greater quantification of selected internal snowpack properties of pack (especially liquid water content). Finally, the potential for combining snow maps from MODIS with snow depth and SWE retrievals from AMSR-E will make a powerful tool for climate studies and global water resource management.